16Nov23

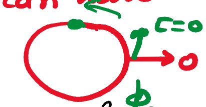
Thursday, November 16, 2023 5:58 PM

Todays class

1. Revision & How to prepare for Exams.

axis
→ displaced in space.
AC voltage - time phase.

"Mexican wave"



ϕ.

Focus AC machines, → Space vector modelling → multiphase

IM PMSM.

AC machine → Rotating field machine : How do we produce rotating fields?

quadrature axis machine.

① 2-phase ... quadrature axis machine.

$\vec{v}_s = v_{s\alpha} + j\, v_{s\beta}$.

ϕ_s - angle between axis of the coil

ϕ_t → time delay of the current

Im, β

$v_\beta = A.\cos(\omega_s t - \pi/2)$

$e^{j\theta} = \cos\theta + j\sin\theta$

α Re

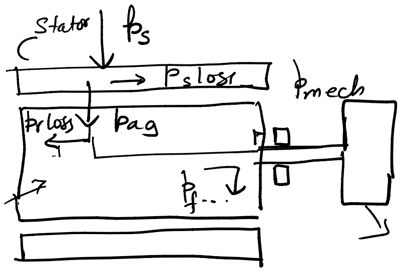
$\phi_s = \pi/2$ $\quad v_\alpha = A.\cos(\omega_s t)$

$\phi_t = -\pi/2$.

② 3-phase ... $\phi_s = 2\pi/3$ $\quad \phi_t = -2\pi/3$.

$v_U(t) = A.\cos(\omega_s t - 0)$, $\quad v_V(t) = A.\cos(\omega_s t - 2\pi/3)$ $\quad v_W(t) = A.\cos(\omega_s t - 4\pi/3)$

$$\vec{v}_s = \frac{2}{3}\left(v_U(t).e^{j0} + v_V(t).e^{j2\pi/3} + v_W(t).e^{j4\pi/3}\right)$$



electric machine

stator system
$$\vec{v}_s^{\,s} = r_s.\vec{i}_s^{\,s} + \frac{d\vec{\psi}_s^{\,s}}{d\tau}$$

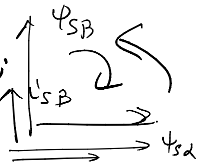
rotor system
$$\vec{v}_r^{\,r} = r_r.\vec{i}_r^{\,r} + \frac{d\vec{\psi}_r^{\,r}}{d\tau}$$

moving - ω.
$$\vec{\psi}_r^{\,s} = \vec{\psi}_r^{\,r}.e^{j\omega\tau} \quad \therefore \vec{\psi}_r^{\,r} = \vec{\psi}_r^{\,s}.e^{-j\omega\tau}$$

rotor eqn into stator coordinats
$$\vec{v}_r^{\,s} = r_r.\vec{i}_r^{\,s} + \frac{d\vec{\psi}_r^{\,s}}{d\tau} - j\omega\vec{\psi}_r^{\,s}.$$

flux linkages
$$\vec{\psi}_s^{\,s} = l_s.\vec{i}_s + l_h.\vec{i}_r = l_h(1+\sigma_s).\vec{i}_s + l_h\vec{i}_r$$
$$\vec{\psi}_r^{\,s} = l_h.\vec{i}_s + l_r.\vec{i}_r. = l_h\vec{i}_s + (1+\sigma_r)l_h.\vec{i}_r$$

$$\boxed{\sigma = 1 - \frac{l_h^2}{l_s.l_r}} \qquad \boxed{\sigma = 1 - \frac{1}{(1+\sigma_s)(1+\sigma_r)}}$$



Torque
$$m_e = \vec{\psi}_s \times \vec{i}_s = \mathrm{Im}\{\vec{\psi}_s^{*}.\vec{i}_s\} \qquad \mathrm{Im}\left[(\psi_{s\alpha} - j\psi_{s\beta}).(i_{s\alpha} + j\, i_{s\beta})\right]$$
$$= (\psi_{s\alpha} + j\psi_{s\beta}) \times (i_{s\alpha} + j\, i_{s\beta}) = \psi_{s\alpha}.i_{s\beta} - \psi_{s\beta}.i_{s\alpha}.$$

Mechanical system
$$T_m.\frac{d\omega}{d\tau} = m_e - m_L$$

IM. 3. Coordinate system

SCS .. stator coordinates system — stationary

β, α

RCS - moves with rotor with ang. vel. = ω.
ε $\quad \therefore \frac{d\varepsilon}{d\tau} = \omega$.

RFCS - moves with rotor fluxlinkage $\vec{\psi}_r^{\,s}$.
ω_s, δ $\quad \therefore \frac{d\delta}{d\tau} = \omega_s$.

electro. $\quad$ SCS. CIM

$$\vec{v}_s^{\,s} = r_s.\vec{i}_s + \frac{d\vec{\psi}_s^{\,s}}{d\tau}$$
$$0 = r_r.\vec{i}_r - j\omega\vec{\psi}_r^{\,s} + \frac{d\vec{\psi}_r^{\,s}}{d\tau}.$$

$$\boxed{\vec{\psi}_s = k_r\vec{\psi}_r + \sigma l_s\vec{i}_s}$$ → This could be represented in any 2 pairs of state variables

1. $\vec{\psi}_s$, $\vec{i}_s$ $\quad$ — $\vec{\psi}_s = l_s.\vec{i}_s + l_h.\vec{i}_r$

2. $\vec{\psi}_s$, $\vec{i}_r$

RFCS - moves with ...
ω_s, δ $\quad \therefore \frac{d\delta}{d\tau} = \omega_s$.

SFCS - moves with $\vec{\Psi}_s^s$, ω_s, δ
$\frac{d\delta}{d\tau} = \omega_s$.

$\vec{\psi}_r$, $\vec{i}_s$ ... SCS ... ODE

$$\frac{d\vec{i}_s}{d\tau} = -\frac{r_k}{\sigma l_s}\vec{i}_s + \frac{k_r}{\sigma l_s \tau_r}(1 - j\omega\tau_r)\vec{\psi}_r + \frac{\vec{v}_s}{\sigma l_s}.$$

$$\frac{d\vec{\psi}_r}{d\tau} = -\frac{1}{\tau_r}\vec{\psi}_r + j\omega\vec{\psi}_r + \frac{1}{\tau_r} l_h \cdot \vec{i}_s$$
$$= -\frac{1}{\tau_r}(1 - j\omega\tau_r)\vec{\psi}_r + \frac{1}{\tau_r} \cdot l_h \cdot \vec{i}_s.$$

$\boxed{m_e = k_r \cdot \vec{\psi}_r \times \vec{i}_s}$ $\qquad \vec{\psi}_s = k_r \vec{\psi}_r + \sigma l_s \cdot \vec{i}_s$

1. $\vec{\Psi}_s$, $\vec{i}_s$
2. $\vec{\Psi}_s$, $\vec{i}_r$
3. $\vec{\Psi}_r$, $\vec{i}_s$
4. $\vec{\Psi}_r$, $\vec{i}_r$
5. $\vec{i}_s$, $\vec{i}_r$
6. $\vec{\Psi}_s$, $\vec{\Psi}_r$

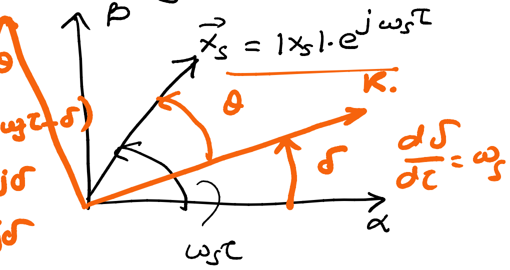
$\vec{\Psi}_s = l_s \cdot \vec{i}_s + l_h \cdot \vec{i}_r$
$\vec{\Psi}_r = l_h \cdot \vec{i}_s + l_r \cdot \vec{i}_r$

practice ... 3 main complex eqns for these combi.

① stator system ② rotor system $\boxed{\vec{\Psi}_s \times \vec{i}_s}$
m_e
③ Mechanical system

Convert into any other coordinates

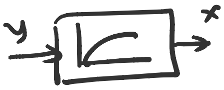
$\vec{x}_s^K = |x_s| e^{j\theta}$
$= |x_s| e^{j(\omega_s\tau - \delta)}$
$\vec{x}_s^K = \vec{x}_s^S \cdot e^{-j\delta}$
$\vec{x}_s^S = \vec{x}_s^K \cdot e^{j\delta}$



Signal flow graphs

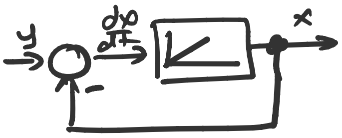
$\frac{dx}{dt} + x = 0.$

$\frac{dx}{dt} + x = y$



$\frac{d\vec{x}}{dt} + \vec{x} = \vec{y}$

$\frac{dx}{dt} = y - x$



Steady-state $\frac{d}{dt} = 0$ ↷ magnitude of vector

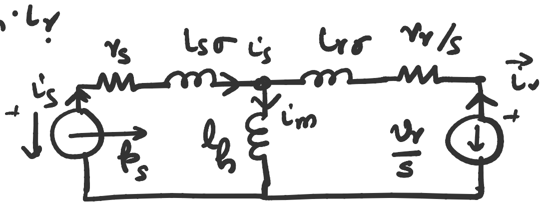
$\vec{v}_s^s = r_s \cdot \vec{i}_s^s + \frac{d\vec{\Psi}_s^s}{d\tau}$ $\qquad \vec{\Psi}_s^s = |\Psi_s| \cdot e^{j\omega_s\tau}$

$\vec{v}_s = r_s\vec{i}_s + j\omega_s \cdot \vec{\Psi}_s = r_s \cdot \vec{i}_s + j\omega_s \cdot l_s \cdot \vec{i}_s + j\omega_s l_h \cdot \vec{i}_r$

$\vec{v}_r = r_r \cdot \vec{i}_r - j\omega(\Psi_r) + j\omega_s \cdot \Psi_r$
$= r_r \cdot \vec{i}_r + j \cdot \omega_r \cdot \vec{\Psi}_r$
$\vec{v}_r = r_r \cdot \vec{i}_r + j\omega_r \cdot l_r \cdot \vec{i}_r + j\omega_r l_h \cdot \vec{i}_s.$

$\omega_r = s\,\omega_s \qquad s = (\omega_s - \omega)/\omega_s.$

$\frac{\vec{v}_r}{s} = \frac{r_r}{s} \cdot \vec{i}_r + j\omega_s \cdot l_r \cdot \vec{i}_r + j\omega_s l_h \cdot \vec{i}_s.$



$\vec{v}_s = r_s \cdot \vec{i}_s + \frac{d\vec{\Psi}_s}{d\tau}.$
SS.
$\vec{v}_s = r_s \vec{i}_s + j\omega_s \vec{\Psi}_s$
$\Psi_s = k_r \Psi_r + \sigma l_s i_s$

2. Types control

1. V/f ... Scalar control

$|v|, f$ → Ψ_s - const
Ψ_r const.

$\boxed{m_e = k_r \vec{\Psi}_r \times \vec{i}_s}$

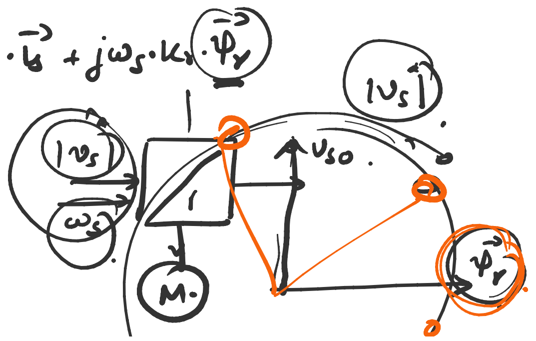
Imp. principle in Torque control of motor.

Steady-state

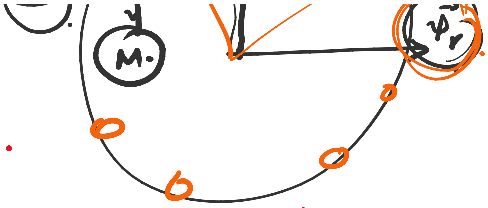
$\vec{v}_s = r_s \cdot \vec{i}_s + j\omega_s \cdot \sigma l_s \cdot \vec{i}_s + j\omega_s \cdot k_r \cdot \vec{\Psi}_r$

$m_e = k_r \cdot \vec{\Psi}_r \times \vec{i}_s$

is scalar
$m_e = k_r \Psi_r \perp \vec{i}_s$



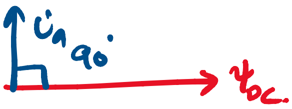
$\boxed{m_e = k_r \Psi_r \times i_s}$ $m_e = k_r \Psi_r \perp \vec{i_s}$



Imp. principle in Torque control of motor.

1. Keep the flux constant.
2. Change the torque producing current.

DC Motor



$m_e = k_r \vec{\Psi_r} \times \vec{i_s}$

torque producing current is always perpendicular to $\vec{\Psi_r}$

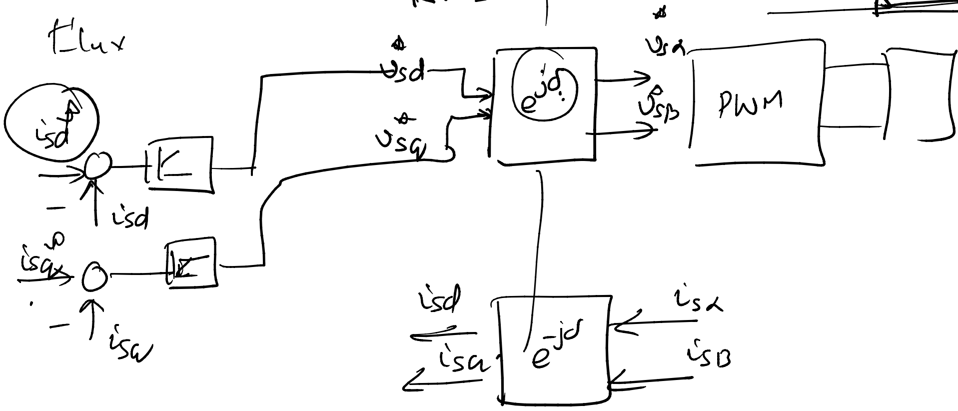
FO vector control

1. FO ... find $\vec{\Psi_r}^s$ and create a d-q coordinate system moving with $\vec{\Psi_r}^s$.

   such that. $\vec{\Psi_r}^s = \Psi_r^F \cdot e^{+j\delta}$ $\quad \vec{\Psi_r}^F = \Psi_{rd} + j0$

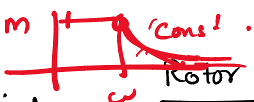
   (a) Stator-equation
   (b) rotor-equation.

2. vector control — RFCS | Stator coordin



PMSM ① Sinusoidal Bm ....

$\Psi_r = \Psi_{rm}$ $\quad \cancel{\Psi_{s0}}$



Rotor geometry defin. $\frac{l_d}{l_q}$

$\Psi_{sd} = \Psi_{rm} + l_d \cdot i_{sd}$.

$\Psi_{sq} = l_q \cdot i_{sq}$.

Machine CPSR

$l_d < l_q$. $\quad l \propto 1/\text{air-gap}$

$m_e = (\vec{\Psi_s} \times \vec{i_s})$

$= (\Psi_{sd} + j\Psi_{sq}) \times (i_{sd} + j\, i_{sq})$

$= \Psi_{sd} \cdot i_{sq} - \Psi_{sq} \cdot i_{sd}$.

$= (\Psi_{rm} + l_d \cdot i_{sd}) \cdot i_{sq} - (l_q \cdot i_{sq}) \cdot i_{sd}$

$= \underbrace{\Psi_{rm} \cdot i_{sq}}_{\text{Synchronous Torque}} + \underbrace{(l_d - l_q)\, i_{sd} \cdot i_{sq}}_{\text{reluctance Torque.}}$

$\boxed{m_e = \Psi_{rm}\, i_{sq} + (l_d - l_q)\, i_{sd} \cdot i_{sq}}$

$m_e > 0$, $i_{sq} > 0$. $i_{sd} < 0$.

$\Psi_{sd} = \Psi_{rm} + l_d \cdot i_{sd}$.

$i_s = \sqrt{i_{sd}^2 + i_{sq}^2}$

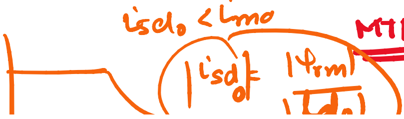
Maximum Torque per Ampere. MTPA

$\frac{dm_e}{d\beta} = 0$.

$i_{sd} = i_{sm} \cdot \sin\beta$

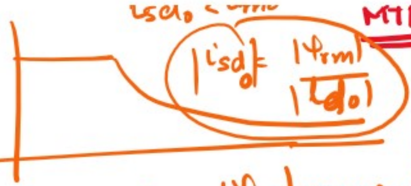
$i_{sq} = i_{sm} \cdot \cos\beta$

$i_{sd_0} < i_{mo}$



MTPA

$i_{sd} = -\frac{\Psi_{rm}}{} - \sqrt{\Psi_m^2 \ldots}$



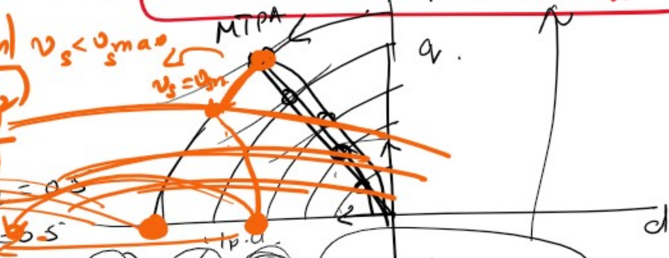
$|i_{sd_0}| = \frac{|\psi_{rm}|}{|l_{d_0}|}$

MTPA

$\underline{i_{sd}} = \frac{-\psi_{rm}}{2(l_d - l_q)} - \sqrt{\frac{\psi_m^2}{4(l_d - l_q)^2} + i_{sq}^2}$

l_d small $|i_{sd_2}| = \frac{|\psi_{rm}|}{|l_{d_2}|}$ $v_s < v_{s\,max}$

$i_{sd_2} > i_{max}$ $|i_{sd_0}| = \frac{|\psi_{rm}|}{|l_d|}$



$m_e = \psi_{rm} \cdot i_{sq} + (l_d - l_q) \cdot i_{sd} \cdot i_{sq}$

$|m_e|$ since $|i_{sq}| > |i_{sd}|$ $(l_d - l_q)$ small

$0.5 =$

BLDC – $\underline{120^\circ}$ conductions.

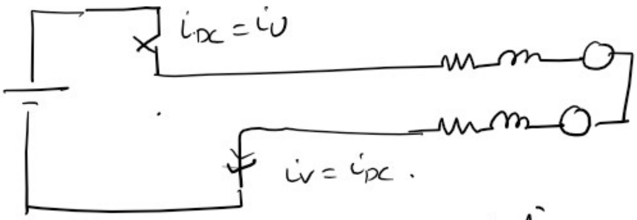
Commutation ripple . . –

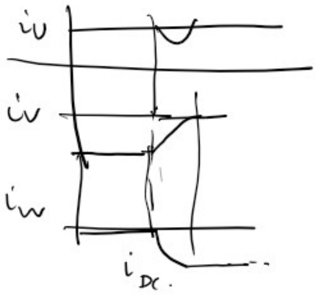
$p_e = e_U \cdot i_U + e_V \cdot i_V + e_W \cdot i_W$

$m_e = \frac{p_e}{\omega}$

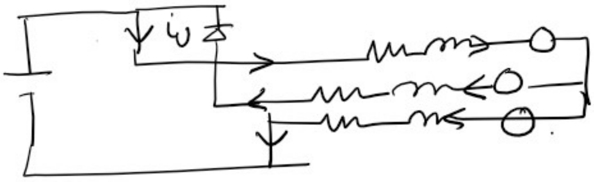
Advantage

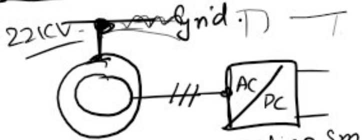
$i_U + i_V + i_W = 0$





intermediate · commutation





① grid voltage high.

②

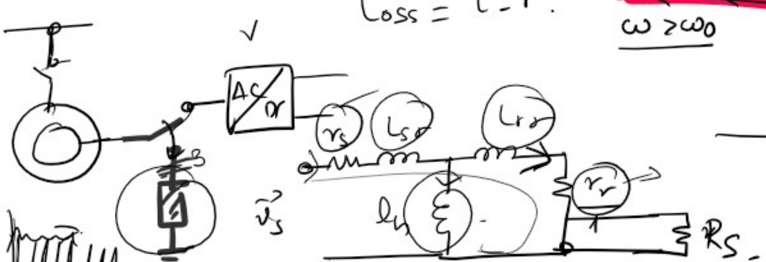
rating smaller.

motoring operation.

$P_{ag} = i_r^2 \cdot \frac{r_r}{s}$.

$P_{cu,s} = s \cdot P_{ag} = i_r^2 \cdot r_r$

$Loss = i^2 \cdot r$.



Steady-state

$\vec{v}_s = r_s \cdot \vec{i}_s + j\omega_s \cdot l_s \cdot \vec{i}_s + j\omega_s \cdot l_h \vec{i}_r$

$\frac{\vec{v}_r}{s} = \frac{r_r}{s} \cdot \vec{i}_r + j\omega_s \cdot l_r \cdot \vec{i}_r + j\omega_s l_h \cdot \vec{i}_s$.

no-load implies $\Rightarrow s = 0 \Rightarrow \vec{i}_r = 0$

no-load implies $\Rightarrow s=0 \Rightarrow \vec{i}_r = 0$

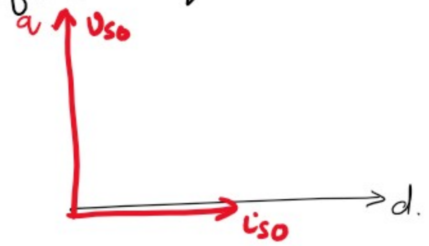
$$\vec{v}_{so} = r_s \cdot \vec{i}_{so} + j\omega_s l_s \cdot \vec{i}_{so} + 0$$

For large power drives. $|v_{so}| >> kV$. drop across r_s $r_s \cdot i_s << |\omega_s l_s| i_{so}|$ $2\pi(50)$

$$\vec{v}_{so} = j\omega_s l_s \cdot \vec{i}_{so} \qquad \vec{v}_{so} = j\omega_s \cdot \vec{\psi}_s$$

$$\boxed{\vec{i}_{so} = \frac{v_{so}}{j\omega_s l_s}}$$

Let us define d-q – SFCS. along $\vec{\psi}_s$



$$\vec{i}_{so} = \frac{\vec{v}_s}{j\omega_s l_s}$$

S.S. state

$$\vec{v}_{so} = j\omega_s l_s \vec{i}_s + j\omega_s l_h \cdot \vec{i}_r$$

$$\frac{\vec{v}_{so}}{j\omega_s l_s} = \vec{i}_s + \frac{j\omega_s l_h}{j\omega_s l_s} \vec{i}_r$$

$$\vec{i}_{so} = \vec{i}_s + \frac{j\omega_s l_h}{j\omega_s l_s} \cdot \vec{i}_r$$

$$\vec{i}_s = \vec{i}_{so}\left[1 - \frac{j\cancel{\omega_s l_s}}{\vec{v}_{so}} \cdot \frac{j\omega_s l_h}{j\omega_s \cancel{l_s}} \cdot \vec{i}_r\right]$$

$$\vec{i}_s = \vec{i}_{so}\left[1 - \frac{\vec{i}_r}{\vec{v}_{so}/j\omega_s l_h}\right]$$

$$\vec{i}_s = \vec{i}_{so}\left[1 - \frac{\vec{i}_r}{\vec{i}_{ms}}\right]$$

② $\vec{i}_s$ & $\vec{i}_r$ flow.

$$\vec{v}_{so} = j\omega_s \cdot l_s \cdot \vec{i}_s + j\omega_s l_h \cdot \vec{i}_r$$

$$= j\omega_s l_h (1+\sigma_s) \cdot \vec{i}_s + j\omega_s l_h \cdot \vec{i}_r$$

$$\vec{v}_{so} = j\omega_s l_h \left[(1+\sigma_s) \cdot \vec{i}_s + \vec{i}_r\right]$$

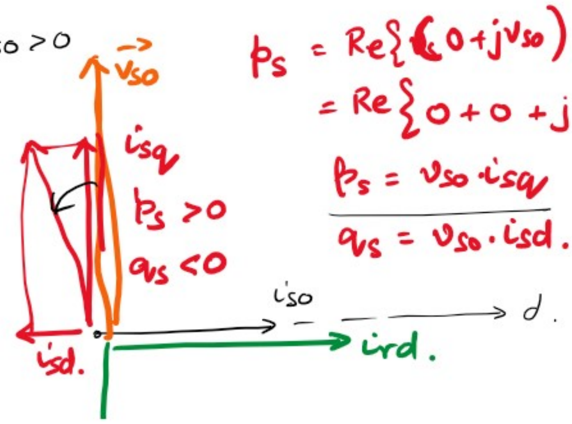
$$\frac{\vec{v}_{so}}{j\omega_s l_h} = (1+\sigma_s) \cdot \vec{i}_s + \vec{i}_r = \vec{i}_{ms}$$

$$\boxed{\vec{i}_s = \vec{i}_{so}\left[1 - \frac{\vec{i}_r}{\vec{i}_{ms}}\right]}$$

$$i_{sd} + j i_{sq} = i_{so}\left[1 - \frac{i_{rd}}{i_{ms}} - j\frac{i_{rq}}{i_{ms}}\right]$$

$$i_{sd} = i_{so}\left[1 - \frac{i_{rd}}{i_{ms}}\right], \quad \cancel{i_{sq} = i_{so}\left[-j\frac{i_{rq}}{i_{ms}}\right]}$$

$q_s < 0$
act like
—||—

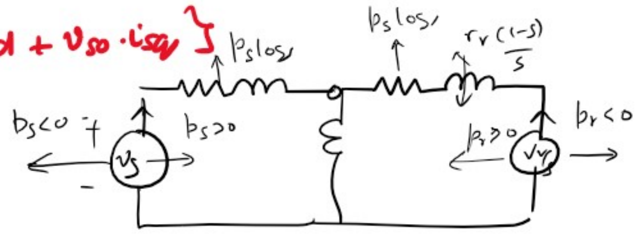


$$p_s = Re\{(0 + jv_{so}) \cdot (i_{sd} - j i_{sq})\}$$

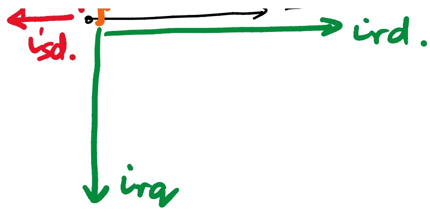
$$= Re\{0 + 0 + j v_{so} \cdot i_{sd} + v_{so} \cdot i_{sq}\}$$

$$p_s = v_{so} \cdot i_{sq}$$

$$q_s = v_{so} \cdot i_{sd}.$$



$4 v_{so}$.



$P_s > 0$

$Q_s > 0$. means acts like

$$\vec{v}_r = r_r \cdot \vec{i}_r + j s \cdot \omega_s \cdot l_r \cdot \vec{i}_r + j s\omega_s \cdot l_m \cdot \vec{i}_s$$

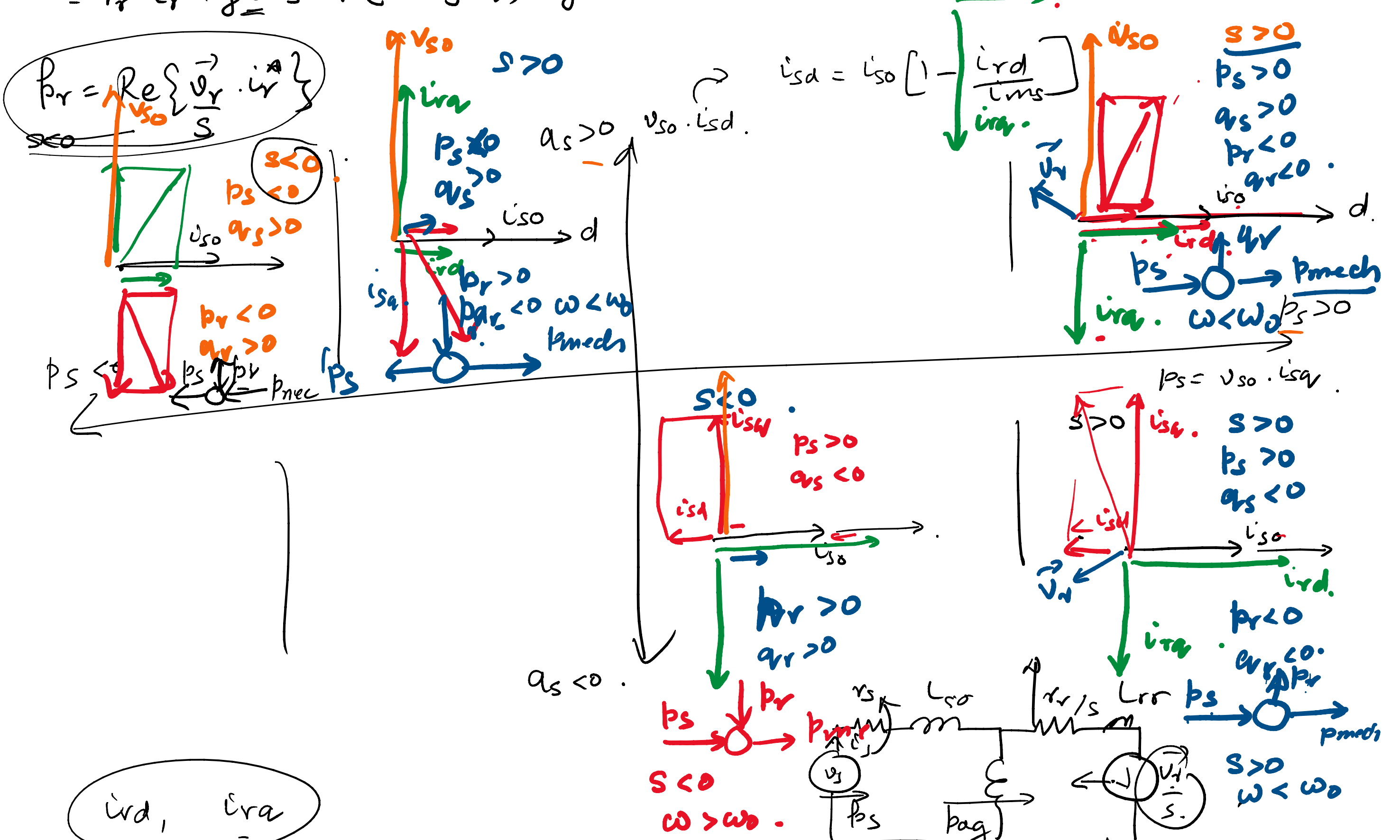
$$= r_r \cdot \vec{i}_r + j s\omega_s\, l_r \cdot (i_{rd} + j i_{rq}) + j s\omega_s l_m \left(i_{so} \left[1 - \frac{i_{rd}}{i_{ms}} \right] - j \frac{i_{rq}}{i_{ms}} \right)$$

$$p_r = \mathrm{Re}\{ \vec{v}_r \cdot \vec{i}_r^{*} \}$$

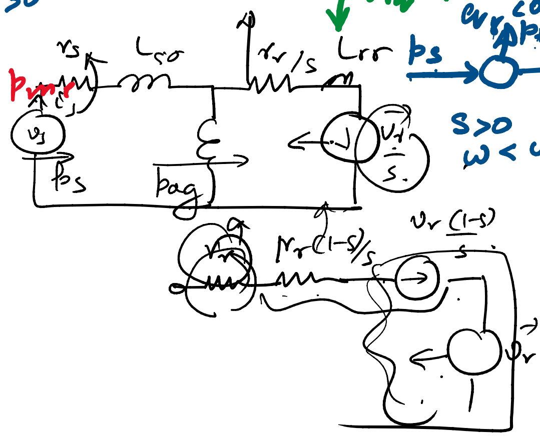
$$i_{sd} = i_{so} \left[1 - \frac{i_{rd}}{i_{ms}} \right]$$

$Q_s > 0$ $v_{so} \cdot i_{sd}$.

$p_s = v_{so} \cdot i_{sq}$.



$Q_s < 0$.



i_{rd}, i_{rq}